

May 5, 2011

Via Electronic Filing

Chairman Julius Genachowski
Commissioner Michael J. Copps
Commissioner Robert M. McDowell
Commissioner Mignon Clyburn
Commissioner Meredith Attwell Baker
Federal Communications Commission
445 Twelfth Street, S.W.
12th Street Lobby, TW-A325
Washington, DC 20554

Re: Written Ex Parte Communication, GN Docket No. 09-51; ET Docket Nos. 10-235, 10-237

Dear Chairman Genachowski, and Commissioners Copps, McDowell, Clyburn, and Baker:

CTIA – The Wireless Association® ("CTIA") takes this opportunity to submit a new report developed by Rysavy Research which demonstrates the U.S. mobile wireless providers are extremely efficient in their use of spectrum, investing massive amounts of capital in their networks through expansions of coverage and capacity, continually developing and embracing innovative network improvements, and utilizing a network architecture that achieves a maximum capacity that is orders of magnitude higher than other wireless systems.

The attached report, *Efficient Use of Spectrum*, analyzes the most relevant ways to measure spectrum efficiency, and details the wireless industry's efforts to develop and deploy new approaches to further spectrum efficiency. Notably, the Rysavy paper concludes that: "By every relevant measure, the US wireless industry uses [its] spectrum extremely efficiently, not only approaching the theoretical limits of what physics allows, but with what is practically achievable with respect to deployment."

Rysavy carefully examines mobile wireless providers efforts to improve their spectral efficiency and states that "no stone is being left unturned in the quest to make wireless networks as efficient as possible." Specifically, the paper notes:

- "Escalating demand, vigorous competition, and spectrum scarcity have driven the U.S.
 wireless industry to procure and spend the capital needed to upgrade and replace their
 networks at a pace significantly faster than the rate of other spectrum users. Indeed, the
 wireless industry has had to bankroll new network technologies every three or four years, on
 average."
- "The U.S. wireless industry employs a range of sophisticated techniques to maximize the efficiency and performance of its networks. For example, modern cellular systems employ a large number of possible modulation and coding methods, changing these dynamically as needed to get the best possible net throughput of data. The combination of modulation and coding can be different for every single user in the network and varied dynamically through



instantaneous adjustments."

• "Among the approaches being developed and deployed are heterogeneous networks, wider radio channels, femtocells, Wi-Fi offload, and cognitive radio. Although these enhancements will continue to increase system capacity, they alone will not address growing demand for mobile wireless services and need for additional spectrum allocations to meet that demand."

The report also investigates the efficiency of cellular systems as compared to other wireless architectures, such as those used to provide broadcast television and mobile satellite services. Rysavy concludes that:

• "Cellular systems, utilizing frequency re-use, can deliver an aggregate capacity that is 30-100 times higher than non-cellular systems, such as broadcast architectures."

This report also finds that, although U.S. mobile wireless providers have achieved enormous levels of efficiency and continue to embrace new spectral efficiency techniques, the enhancements laid out in this report will not alone address the growing demand for mobile wireless services. As Rysavy explains, "[i]ncreasing data spectral efficiency is extremely important for increasing network capacity, but, by itself, it is not enough to address the burgeoning demand for capacity for mobile-broadband services." Thus, CTIA urges the Commission to continue its commitment to identifying additional spectrum for mobile broadband.

As the Commission has recognized, mobile broadband services are increasingly vital to advancing many interests including education, health, public safety, and our economy. CTIA offers the attached report to update the FCC as to the varied approaches the wireless industry has taken to measure and improve spectrum efficiency. This report provides yet further evidence that, while the U.S. wireless industry is doing everything it can to use the currently allocated spectrum efficiently, identifying additional spectrum as quickly as possible for mobile broadband services is of critical importance.

Pursuant to Section 1.1206 of the Commission's rules, a copy of this letter is being filed via ECFS with the FCC Secretary's Office. If you have any questions, please do not hesitate to contact me.

Sincerely,

/s/ Christopher Guttman-McCabe
Christopher Guttman-McCabe
Vice President, Regulatory Affairs
CTIA – The Wireless Association®

Attachment

1. Efficient Use of Spectrum, Rysavy Research (May 4, 2011)



Efficient Use of Spectrum

May 4, 2011

About Rysavy Research

Rysavy Research LLC is a consulting firm that has specialized in wireless technology since 1993. Projects have included reports on the evolution of wireless technology, spectrum analysis for broadband services, evaluation of wireless technology capabilities, strategic consultations, system design, articles, courses and webcasts, network performance measurement, and test reports.

Peter Rysavy, president of Rysavy Research, specializes in the capabilities and evolution of wireless technology. He has written more than a hundred and twenty articles, reports and white papers, and has taught forty public wireless courses and webcasts. He has also performed technical evaluations of many wireless technologies including municipal/mesh Wi-Fi networks, Wi-Fi hotspot networks, mobile browser technologies, 3G networks, and wireless e-mail systems.

From 1988 to 1993, Peter Rysavy was vice-president of engineering and technology at LapLink where projects included LapLink, LapLink Wireless, and connectivity solutions for a wide variety of mobile platforms. Prior to that, he spent seven years at Fluke Corporation where he worked on touch screen and data acquisition products.

Peter Rysavy is also the executive director of the Portable Computer and Communications Association (PCCA, http://www.pcca.org), a group that evaluates wireless technologies, investigates mobile communications architectures and promotes wireless-data interoperability. Peter Rysavy graduated with BSEE and MSEE degrees from Stanford University in 1979. More information is available at http://www.rysavy.com.

Notice

Rysavy Research provides this document and the information contained herein to you for informational purposes only. Rysavy Research provides this information solely on the basis that you will take responsibility for making your own assessments of the information.

Although Rysavy Research has exercised reasonable care in providing this information to you, Rysavy Research does not warrant that the information is error-free. Rysavy Research disclaims and, in no event, shall be liable for any losses or damages of any kind, whether direct, indirect, incidental, consequential, or punitive arising out of or in any way related to the use of the information.

Table of Contents

INTRODUCTION	4
SPECTRAL EFFICIENCY	5
FUNDAMENTAL MEASURES	
How Spectral Efficiency Improves	10
Shannon Bound	11
NETWORK EVOLUTION	13
Heterogeneous Networks	13
Wider Radio Channels	14
FEMTOCELLS	14
WI-FI OFFLOAD	
Cognitive Radio	15
EFFICIENCY OF CELLULAR SYSTEMS COMPARED TO OTHER SYSTEMS	16
COMPARISON WITH BROADCAST-TELEVISION SYSTEMS	16
COMPARISON WITH MOBILE SATELLITE SYSTEMS	
GROWTH IN CAPACITY OVER TIME	18
SERVICES DELIVERED	20
VOICE MINUTES	
Message Volume	22
Data Volume	22
APPLICATION EFFICIENCY	24
CONCLUSION	25

Introduction

Given the tremendous demand for spectrum, it is essential that the use of spectrum be efficient. This CTIA-sponsored paper analyzes how efficiently the U.S. wireless industry uses its Commercial Mobile Radio Service (CMRS) spectrum. By every relevant measure, the U.S. wireless industry uses this spectrum extremely efficiently, not only approaching the theoretical limits of what physics allows, but with what is practically achievable with respect to deployment.

Today's wireless technologies operate with high spectral efficiency and today's cellular architectures inherently deliver services to large numbers of people in an extremely efficient manner. As described in this paper, no stone is being left unturned in the quest to make wireless networks as efficient as possible.

There are a variety of ways to gauge how efficiently spectrum is being used, and this paper analyzes the most relevant measures. First, and at the most fundamental radio level, one can measure and compare the efficiency of the radio-air interface. Measuring how much digital data can be encoded (measured in bits per second) in a certain amount of spectrum is a key measure of spectral efficiency and is discussed in the next section. This paper demonstrates that the U.S. wireless industry is doing a remarkable job of implementing new radio capabilities as quickly as possible, and that, by this measure, the industry is reaching the theoretical limits of spectral efficiency.

Another, more holistic, way of analyzing spectrum efficiency is to look at the density of bits delivered across geographical areas: this measure may better capture the overall efficiency of an entire wireless network. Because cellular networks inherently have high frequency re-use, they achieve huge efficiencies in how much data they can deliver to any specific area, far greater than alternate approaches. By employing sophisticated techniques, such as frequency re-use, U.S. cellular networks offer a maximum capacity that is between thirty and one hundred (30 and 100) times greater than single-coverage architectures, like broadcast-television networks. How and why this is the case is also covered in this paper.

Another valuable way of assessing use of spectrum is to consider how many services a wireless network delivers to how many subscribers over a certain amount of spectrum. Services refer to items such as voice minutes, text messages, and Internet access. This paper discusses this approach in detail and presents data to show that the U.S. leads the world in delivered services.

This paper also examines the wireless industry's continuing efforts to develop and deploy promising new approaches that further improve how efficiently spectrum is used. Spurred by consumer demand and competition, the U.S. wireless-industry has engaged in—and continues to develop—a progressive series of enhancements to leverage emerging capabilities and deployment methods.

As discussed more fully below, key findings of this report include:

- Overall, the wireless industry is doing an extraordinary job of implementing new radio capabilities as quickly as is possible. Witness, for example, the wide availability nationwide of 3G and the leading role of U.S. providers in deploying 4G capabilities. By and large, every practical radio innovation known is being implemented into today's standards.
- Escalating demand, vigorous competition, and spectrum scarcity have driven the U.S. wireless industry to procure and spend the capital needed to upgrade and replace their networks at a pace significantly faster than the rate of other spectrum users. Indeed, the wireless industry has had to bankroll new network technologies every three or four years, on average.
- Over the last twenty-four years, voice capacity over U.S. wireless networks has increased by a
 multiplicative combination of cell-site density and voice spectral efficiency. By increasing cellsite density and voice spectral efficiency, the total network capacity has increased 4,708-fold
 since 1985.
- The U.S. wireless industry employs a range of sophisticated techniques to maximize the
 efficiency and performance of its networks. For example, modern cellular systems employ a
 large number of possible modulation and coding methods, changing these dynamically as
 needed to get the best possible net throughput of data. The combination of modulation and
 coding can be different for every single user in the network and varied dynamically through
 instantaneous adjustments.
- Unfortunately, the continual advances in spectral efficiency the industry has been able to achieve will not be able to persist forever due to fundamental constraints of physics expressed in the Shannon Bound. The Shannon Bound is a theoretical limit on the bps/Hz that can be achieved relative to noise.
- Cellular systems, utilizing frequency re-use, can deliver an aggregate capacity that is 30-100 times higher than non-cellular systems, such as broadcast architectures.
- In the last twenty-five years, the number of cell sites in the U.S. has increased from 913 to 253,086, representing a 277-fold increase in capacity due to frequency re-use alone.
- Among the approaches being developed and deployed are heterogeneous networks, wider radio channels, femtocells, Wi-Fi offload, and cognitive radio. Although these enhancements will continue to increase system capacity, they alone will not address growing demand for mobile wireless services and need for additional spectrum allocations to meet that demand.

Spectral Efficiency

To explain spectral efficiency, this section details how spectral efficiency values are derived, how they increase over time, and the ultimate limits of what technology can achieve in what is called the Shannon Bound.

Fundamental Measures

The fundamental measure of spectral efficiency is the bits per second (bps) obtained relative to Hertz (Hz) of spectrum used (bps/Hz). A primary factor in spectral efficiency is the type of radio

modulation used. Radio modulation involves modifying a radio waveform over an interval of time to encode bits of information. This modulated waveform is called a symbol. For instance, if a symbol can occupy four different phase (delay) states, then it encodes two bits of binary data. Higher-order modulation used in WiMAX or LTE such as 64 Quadrature Amplitude Modulation (QAM) encodes six bits of data in each symbol.

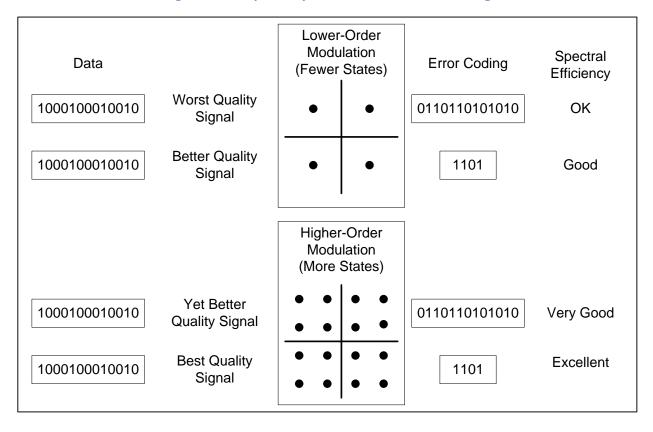
It is not possible, however, to just use the highest-order modulation available, because there is a tradeoff between modulation efficiency and signal quality. Higher-order modulation generally requires a signal that has a higher signal-to-interference ratio. For the same level of interference, a higher-order modulation scheme results in a larger percentage of bits decoding incorrectly.

Some of these errors can be corrected through what is called coding, a process by which additional redundant bits inserted in the transmission allow mathematical algorithms in the receiver to reconstruct the original data when there are errors during transmission. This coding makes digital communication of data much more reliable, but it introduces an overhead factor that reduces the effective communications rate. So there is a tradeoff between the modulation method used and the amount of coding. Given widely varying radio conditions in terms of signal strength and amount of interference, modern cellular systems employ a large number of possible modulation and coding methods, changing these dynamically as needed to get the best possible net throughput of data. This is a key attribute that characterizes current wireless systems from earlier ones and, by itself, is an illustration of how modern wireless systems use spectrum as efficiently as possible.

Figure 1 provides an example of dynamic modulation and coding. The data is the same for the four scenarios. With the worst quality signal, the system uses a robust, but spectrally less-efficient modulation in combination with a high level of error coding. With a better quality signal, the same modulation is used but with less error coding, hence less communication overhead and better net spectral efficiency. With a yet better signal, the system can employ higher-order modulation in combination with a high level of error coding, resulting in yet improved spectral efficiency. Finally, with the best-quality signal, the system uses both higher-order modulation and the least amount of coding, resulting in the highest possible spectral efficiency.

¹ That is because two bits represent four possible states: 00, 01, 10, and 11. Similarly eight phase states would encode three bits of data: 000, 001, 010, 011, 100, 101, 111.

Figure 1: Example of Dynamic Modulation and Coding



The combination of modulation and coding can be different for every single user in the network. In fact, in advanced systems such as High Speed Packet Access (HSPA) or Evolved Data Optimized (EV-DO), the base station scheduler will decide which users to transmit to based on their instantaneous radio conditions, favoring those that have better signal quality at that moment in time, thus improving efficiency of the overall cell. This is a further example of the sophistication of today's wireless technologies, and the efforts expended to maximize efficiency.

"...the base station scheduler will decide which users to transmit to based on their instantaneous radio conditions, favoring those that have better signal quality at that moment in time, thus improving efficiency of the overall cell."

Sometimes spectral efficiency of a technology is quoted based on its peak achievable spectral efficiency, namely the spectral efficiency that can be achieved under relatively ideal radio conditions. What is more useful, however, is to know what the overall network can deliver.

Vendors and operators determine network spectral efficiency by performing complex computer simulations that model a network with multiple users distributed across the cell-site coverage area. Based on each user's predicted signal quality, the mathematical model determines what

modulation/coding scheme they can use. The models take into account that there are other users, as well as neighboring cell sites, using the same frequencies and generating interference. By looking at the aggregate throughput for each user, the model can calculate a cell throughput value with a corresponding bps/Hz value. This is an extremely useful measure because it informs, on a system level, how many subscribers a network can support with what types of services. Since many cells today are divided into sectors each with a separate radio, the spectral efficiency is usually calculated on a per sector basis.

For example, a technology that has downlink spectral efficiency of 1.0 bps/Hz/sector means that in a frequency-division duplex deployment of 5 MHz for the downlink (forward direction) and 5 MHz for the uplink (reverse direction), the downlink in each sector would have an aggregate capacity of 5 Mbps. This value is simply obtained by multiplying the 5 million Hz by the 1.0 bps/Hz value. For a three-sector cell, this equates to a total downlink cell capacity of three times 5 Mbps, or 15 Mbps.

Rysavy Research has done extensive comparative analysis of the spectral efficiency of different technologies in multiple projects dating back to 2002. The most recent results are published in a white paper for 3G Americas titled "Transition to 4G - 3GPP Broadband Evolution to IMT-Advanced." The spectral efficiency values shown in this paper are based on a consensus analysis involving multiple vendors and operators.

All the wireless technologies have migration paths that continually increase spectral efficiency. For example, CDMA2000 Evolved Data Optimized (EV-DO) and High Speed Packet Access (HSPA) as initially deployed had spectral efficiency of about 0.75 bps/Hz/sector. With various available enhancements, however, networks will be able to eventually double spectral efficiency to 1 bps/Hz. LTE has spectral efficiency of 1.5 bps/Hz, and with more advanced Multiple Input Multiple Output (MIMO) antenna configurations, will achieve values as high as 2.4 bps/Hz. For a network employing 10 MHz by 10 MHz, that would mean 24 Mbps per sector.

Spectral efficiency increases further with systems that are based on the IMT-Advanced requirements that have been issued by the International Telecommunications Union (ITU). The specifications mandate an average downlink spectral efficiency value of 2.2 bps/Hz and a peak spectral efficiency value of 15 bps/Hz. A future version of LTE, called LTE-Advanced, is being designed to meet the IMT requirements, as is a future version of WiMAX called WiMAX 2 that is based on the IEEE 802.16m specification. Figure 2 summarizes the cited spectral efficiency values.

² Spectral efficiency analysis is on page 51 of Rysavy Research, "Transition to 4G," September, 2010. http://www.rysavy.com/Articles/2010_09_HSPA_LTE_Advanced.pdf

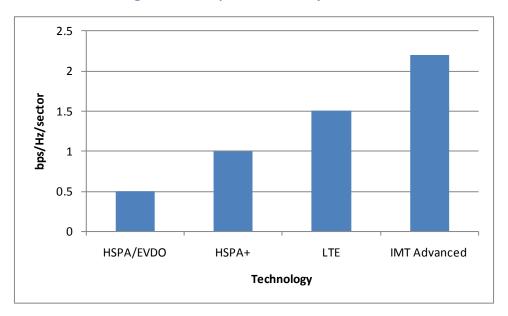


Figure 2: Data Spectral Efficiency Evolution

Uplink spectral efficiency for most wireless systems is lower than downlink spectral efficiency, often at about half of the downlink value. This is partially because mobile devices transmit at lower power than the base station. In addition, multiple devices each with their own separate radio must be carefully coordinated to share the radio channel, compared to the downlink where there is just the base station radio. Finally, it is expected that the number of transmitters in the downlink will typically be more than the number of transmitters within a device and so the downlink capacity has the advantage of using MIMO to provide higher throughput.

Increasing data spectral efficiency is extremely important for increasing network capacity, but, by itself, it is not enough to address the burgeoning demand for capacity for mobile-broadband services. Rysavy Research projections for increased spectrum needs already assume that newer technologies with higher spectral efficiency will be aggressively deployed.³

While much of the current policy debate focuses on meeting the growing demand for mobile broadband services, the U.S. wireless industry's history of innovation is illustrated by its handling of voice traffic, as well. Voice spectral efficiency has improved steadily with successive technologies. Digital-cellular systems significantly increased spectral efficiency over analog systems. Additional

³ For further details, refer to Rysavy Research, "Mobile Broadband Capacity Constraints and the Need for Optimization," February 24, 2010.

gains have become possible with more advanced digital voice coding/decoding (codec) systems. Figure 3 shows the improvements in voice spectral efficiency over time as measured in Erlangs⁴.

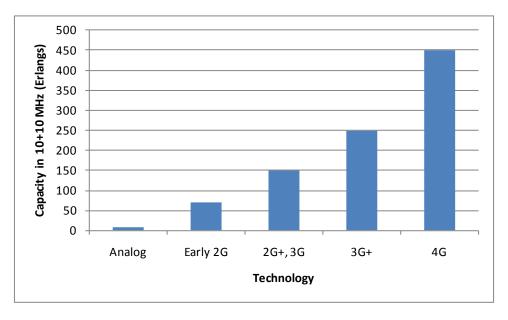


Figure 3: Voice Spectral Efficiency Evolution

How Spectral Efficiency Improves

There are a variety of methods being used to progressively improve spectral efficiency. Some of the most important ones are as follows:

- **Higher-Order Modulation.** This is used in 2G, 3G, enhanced 3G, WiMAX and LTE. As noted above, there is a tradeoff between modulation efficiency and signal quality. Thus, U.S. wireless carriers deploy sophisticated methods to dynamically achieve the best possible net throughput.
- Advanced Antenna Systems. Technologies such as LTE and WiMAX rely on advanced antenna systems to significantly increase spectrum efficiency. The most common initial type is Multiple Input Multiple Output (MIMO), which relies on signals propagating through

Note: Erlangs are a measure of voice carrying capacity approximately representing the number of concurrent calls that the network can support in a specified amount of spectrum.

⁴ Source: Rysavy Research, "Voice Capacity Enhancement for GSM Evolution to UMTS," July 18, 2002. http://www.rysavy.com/Articles/GSM_voice_capacity_71802.pdf, and Rysavy Research, "Transition to 4G," September, 2010. http://www.rysavy.com/Articles/2010_09_HSPA_LTE_Advanced.pdf.

environments along multiple paths. LTE technology employs other advanced antenna methods, including beam steering.

- **Equalization and Interference Cancellation.** These methods improve the quality of the radio signal prior to demodulation and coding, allowing more aggressive modulation and coding.
- Orthogonal Frequency Division Multiple Access (OFMDA). WiMAX and LTE are based on a
 multiplexing approach called OFDMA as opposed to the Code Division Multiple Access that
 is used in most 3G systems. OFDMA provides some fundamental implementation
 advantages, facilitating the deployment of systems with high spectral efficiency.

All of the technology families including 3GPP, 3GPP2, and WiMAX take advantage of the methods described. Each successive release of specifications adds new features and capabilities geared towards higher performance and efficiency. Some of these, e.g., MIMO, are quite complex to implement. For example, many of these innovations must also be implemented on both sides of the radio link. This can be challenging in the small form factors of handheld devices.

Overall, the wireless industry is doing an extraordinary job of implementing new radio capabilities as quickly as is feasible, for example, the wide availability nationwide of 3G. By and large, every practical radio innovation known is being implemented into today's standards. No stone is being left unturned in the guest to make wireless networks as efficient as possible.

Escalating demand, vigorous competition, and spectrum scarcity have driven the U.S. wireless industry to procure and spend the capital needed to upgrade and replace their networks at a pace significantly faster than the rate of other spectrum users. Indeed, the wireless industry has had to bankroll new network technologies every three or four years, on average. U.S. wireless carriers have also had to develop features and services that entice subscribers to replace their handsets at the same or faster pace. This kind of rapid innovation does not happen in military, public safety, broadcast, long-haul microwave, satellite, or any other wireless spectrum class.

Shannon Bound

Unfortunately, the continual advances in spectral efficiency the industry has been able to achieve will not be able to persist forever due to the fundamental constraints of physics expressed in the Shannon Bound. The Shannon Bound is a theoretical limit on the bps/Hz that can be achieved relative to the signal-to-noise ratio (SNR). As shown in Figure 4, all of today's advanced wireless technologies are within 2 or 3 decibels of this bound, meaning they are almost as close as can be achieved in practical technology implementations.

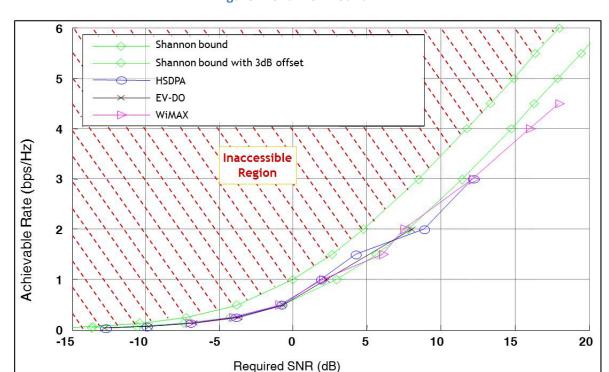


Figure 4: Shannon Bound⁵

This does not mean that no further spectral-efficiency gains are possible. Techniques like smart antenna technologies allow further gains and are being implemented with the migration to 4G. These technologies do, however, come at significant system complexity and cost, and have limits of their own. For example, MIMO effectively creates multiple transmission paths through the environment, each individually constrained by the Shannon bound, but resulting in an overall increase in spectral efficiency. With LTE, for instance, a 4X4 antenna configuration⁶ will provide approximately a 50% gain in spectral efficiency over a 2X2 configuration.⁷ Another example is with beam-steering technologies. By focusing the base station radio beam on a particular user, the link has a higher SNR and, hence, a higher available spectral efficiency.

As the wireless industry migrates from current 3G systems to enhanced 3G (e.g., HSPA+, EV-DO Advanced) to 4G systems, all of these spectral-efficiency methods—including higher-order modulation, advanced antenna systems, OFDMA, interference cancellation—are being implemented.

⁵ Source: courtesy Alcatel Lucent.

⁶ 4 transmit antennas, 4 receive antennas

⁷ Source: Rysavy Research, "Transition to 4G," September, 2010. http://www.rysavy.com/Articles/2010 09 HSPA LTE Advanced.

But the industry is reaching the limits of such gains. There are also practical considerations. With MIMO, for example, the antennas must be spaced far enough apart for independent transmissions to occur. In smaller handset devices, this may simply not be possible, especially at lower frequencies (e.g., 700 MHz) which translate to larger wavelengths and, hence, larger antenna separation.

Network Evolution

As the industry moves forward, U.S. wireless carriers are actively developing and implementing new technical developments worth noting that have the potential to further improve wireless spectrum usage beyond the ones discussed so far. These include developments in heterogeneous networks, wider radio channels, femtocells, Wi-Fi offload, and cognitive radio. These techniques demonstrate the U.S. wireless industry's commitment to innovation and efficiency, and represent pursuing every path possible to boost capacity based on available technology and spectrum. By themselves, however, they still will not meet the escalating capacity demands of mobile broadband users, a demand that can only be met through a combination of advanced technology, aggressive frequency re-use, and additional spectrum.

Heterogeneous Networks

There is no one wireless topology that meets all requirements. For example, cell sites that cover large areas (macro cells) permit a lower-cost network deployment, but have lower overall capacity and, hence, can serve fewer subscribers. Pico cells, in contrast, can handle large subscriber density, but each cell only serves a small coverage area. Femtocells, discussed below, cover even smaller coverage areas. Meanwhile, each of these types of cells can operate at multiple frequency bands, and can potentially employ multiple technologies (2G, 3G, 4G.) Then there are unlicensed bands for Wi-Fi, increasingly supported by mobile devices and increasingly used by operators for offloading data. It is through a combination of networks, as illustrated in Figure 5, that operators will be able to best satisfy user needs, to best manage capacity requirements against escalating demand, and to use spectrum most efficiently. There are a number of standards that permit heterogeneous network operation including 3GPP Integrated Wireless LAN⁸, Generic Access Network⁹, and IEEE 802.21¹⁰.

⁸ The specification is 3GPP TS 23.234, "3GPP System to Wireless Local Area Network (WLAN) Interworking," http://www.3gpp.org/ftp/Specs/html-info/23234.htm

⁹ The specification is 3GPP TS 43.318, "Radio Access Network: Generic Access Network," http://www.3gpp.org/ftp/Specs/html-info/43318.htm

¹⁰ The specification is IEEE Std 802.21, "IEEE Standard for Local and Metropolitan Area Networks: Media Independent Handover Services."

Achieving this network integration, and masking the complexity from users, is a hugely challenging task, but one in which the industry is heavily engaged. For example, 3GPP has a standards initiative for self-organizing and self-optimizing networks, an essential element for networks that adapt dynamically in real-time to changing load, varying applications, interference, and new sites.

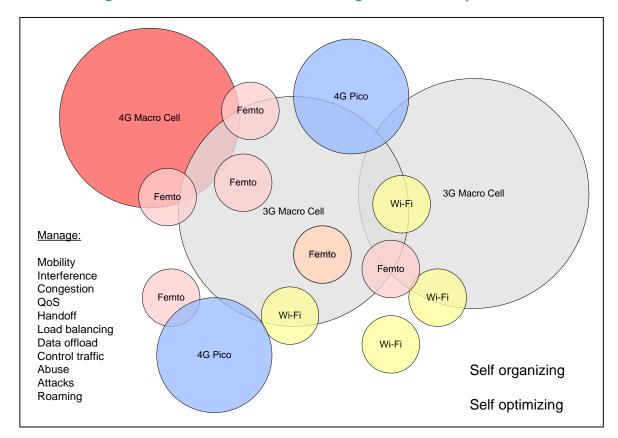


Figure 5: Network of Networks that Self Organizes and Self Optimizes

Wider Radio Channels

Another way of increasing efficient use of spectrum is the deployment of technologies in wider radio channels. The wireless industry has a long history of increasing radio channel widths. Analog cellular used 30 kHz channels, 2G systems such as GSM use 200 kHz, 3G systems use 1.25 MHz or 5 MHz, WiMAX and LTE in current deployments use 10 MHz with LTE capable of using up to 20 MHz, and LTE-Advanced will use up to 100 MHz through channel aggregation. Wider radio channels not only provide higher peak data rates, but can achieve higher spectral efficiency.

Femtocells

As discussed earlier, higher frequency re-use is one of the most effective means possible to boost overall network capacity. In this regard, femtocells are increasingly playing a pivotal role since they represent the smallest possible coverage areas for licensed bands. AT&T, Sprint, and Verizon have

all launched femtocell service. Over time, however, femtocells will play an increasingly important role in offloading traffic from the macro cellular network and increasing overall system capacity.

Wi-Fi Offload

Operators, including AT&T, T-Mobile, and Verizon, are offloading some of their data traffic from the cellular network onto Wi-Fi networks. This is increasingly feasible as more mobile devices are Wi-Fi capable. Offload can be onto hotspot networks as well as onto private networks. Various standards, such as 3GPP Integrated Wireless LAN, provide for tight integration between Wi-Fi and cellular networks, allowing for a seamless user experiences in which data applications continue to function even as the device traverses between different network types.¹¹

Cognitive Radio

Going forward, cognitive radio technology is being deployed as a means of communication that avoids interference with licensed or unlicensed users. It is based on the premise that since some bands are lightly used, or only used in some geographic areas, other devices can use the spectrum so long as they employ mechanisms to ensure they do not interfere with the primary users. For instance, the IEEE 802.22 working group is developing a standard to enable operation in unused television channels.¹²

Another example is GSM technology that has the ability to do automatic channel assignments based on interference levels in the network. These types of automatic solutions are being used to increase the overall spectral efficiency throughout the network. For mobile cellular networks, in particular, cognitive techniques appear to be best deployed within the licensed spectrum as opposed to between licensed and unlicensed users. Attempting to deploy opportunistic sharing by unlicensed users in licensed spectrum could actually decrease the spectral efficiency within the network due to interference that reduces capacity. Moreover, such an approach has additional drawbacks. For example, not knowing when and how users will be using the bands leads to uncertainty in engineering and deployment, which strongly counsels against the deployment of opportunistic sharing methods by unlicensed users in licensed spectrum.

Cognitive radio is a promising longer term approach to obtain greater efficiency from bands that are not heavily used. Reliable radio communications, however, is a delicate proposition under normal conditions. Guaranteeing correct operation when diverse sets of users access spectrum will require considerable development and evaluation.

¹¹ For more details on Wi-Fi offload, refer to the Rysavy Research white paper, "Strategic Use of Wi-Fi Mobile Broadband Networks," October 2010. http://www.rysavy.com/Articles/2010 10 Strategic Wi-Fi.pdf

¹² For working group details, refer to http://www.ieee802.org/22/.

Efficiency of Cellular Systems Compared to Other Systems

In the United States, policymakers have allocated spectrum not only to the cellular communications industry, but also to other wireless services that deploy very different wireless architectures. Examples of other wireless architectures include point-to-point microwave systems or broadcasting systems, such as broadcast television and radio.

It is possible to determine the radio-interface efficiency for many different wireless architectures and wireless technologies, but this measurement is a poor means of comparing the relative efficiency of those different architectures. While it is possible with alternate architectures to achieve higher radio interface values than in cellular systems, this does not mean that they use spectrum more efficiently. Quite the contrary, one must look at the entire system from the point of view of the total data (or services) delivered across the entire coverage area. As illustrated below, an examination of efficiency across the entire wireless network shows that U.S. cellular systems, thanks largely to frequency re-use, achieve a maximum capacity that is up to orders of magnitude higher than single-coverage systems like broadcast-television networks.

Frequency re-use has contributed more to wireless capacity in today's commercial mobile radio service than any other approach. Frequency re-use refers to using a radio channel in one location, and then re-using it in a nearby location. Today's 3G networks operate in what is called frequency re-use of 1, meaning that every cell sector uses the same frequency channel(s), as well as adjacent cells using the same frequencies. Since radio signals do not stop propagating at the edge of a cell, they continue into the next cell, which creates inherent interference in cellular systems. Although that interference results in lower spectral efficiency for each individual radio channel, it is more than made up for, because there are so many cells. As shown below, the massive investment of the wireless industry in cell sites, and the technique of frequency re-use, have together fueled an enormously efficient U.S. cellular communications industry.

Comparison with Broadcast-Television Systems

One can assess the effectiveness of the cellular approach with frequency re-use by comparing it with other architectures such as that used by broadcast television. Consider the example shown in Figure 6. The single, large-coverage system (noncellular) operates with a spectral efficiency of 3 bps/Hz while the cellular system operates with a spectral efficiency of 1 bps/Hz/sector. The example further assumes 10 MHz of spectrum. The large-coverage system will thus deliver 10 MHz X 3 bps/Hz, or 30 million bits per second (Mbps) of capacity across the coverage area.

In contrast, the cellular system will deliver 10 MHz X 1 bps/Hz, or 10 Mbps to each sector. Each cell consists of three sectors, making for 30 Mbps per cell. The coverage area shown has 30 cells, so the aggregate capacity over the coverage area is 900 Mbps. Thus, the non-cellular system delivers 30

million bps, while the cellular system delivers 900 million bps. That is **30 times** higher than the single- coverage system.

With typical cell site spacing of 1 km, a large metro area could actually have significantly more cells than 30, representing an even greater system capacity. For example, a metropolitan area could easily have 100 cell

"For example, a metropolitan area could easily have 100 cell sites, resulting in aggregate capacity close to 100 times that of a single transmitter."

sites, resulting in aggregate capacity close to 100 times that of a single transmitter.

This analysis does not even take into account that some alternate wireless architectures—like broadcast television—require buffers on each side of their transmission channel, effectively doubling or even tripling the amount of spectrum they use, thus *reducing their spectral efficiency to a half or a third*.

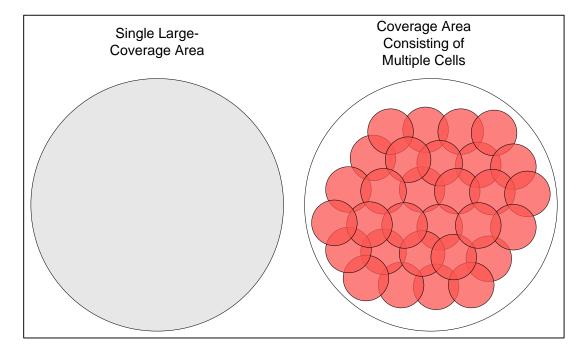


Figure 6: Cellular Approach to Coverage Compared to Single Large-Coverage Area

Comparison with Mobile Satellite Systems

Another point of comparison is with mobile satellite systems. The simplest way to compare is to look at total number of subscribers versus the amount of spectrum allocated. In the U.S., there are,

at most, 2 million MSS subscribers¹³ with 90 MHz of spectrum allocated.¹⁴ This represents about 22,000 subscribers per MHz of spectrum. In contrast, there are approximately 300 million wireless subscribers¹⁵ in 354 MHz of available commercial mobile radio spectrum. This equates to roughly 855,000 wireless subscribers per MHz of spectrum, a value that is over 38 times greater than for mobile satellite systems.

Growth in Capacity over Time

As the number of cell sites increases (as shown in Figure 7), aggregate capacity increases correspondingly. In the last twenty-five years, the number of cell sites in the U.S. has increased from 913 to 253,086, representing a 277-fold increase in capacity due to frequency re-use alone.

¹³ Source: Northern Sky Research, "Mobile Satellite Services Industry Stretched But Sees Fortunes Turning Around," Tuesday, 17 August 2010.

¹⁴ Source: FCC, "National Broadband Plan," 2010, page 84.

¹⁵ Source: CTIA, "Wireless Quick Facts," June 2010.

253,086

251,688

247,081

245,912

241,329

210,500

110,500

113,508

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

114,509

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

115,511

Figure 7: Reported Cell Sites in the US over Time¹⁶

Chart 41: Reported Cell Sites in Commercial Use: 1985 - 2010

167

Materials in this report may not be reproduced or photocopied in any form without written permission from CTIA. The Wireless Association®

Combined with much greater spectral efficiency over each radio channel used, network capacity has grown even faster. To quantify this effect for voice service, consider that early analog voice systems had spectral efficiency of 9 Erlangs/sector in 10 MHz, as shown previously in Figure 3. Meanwhile, today's 2G and 3G systems have increased voice spectral efficiency to about 150 Erlangs/sector in 10 MHz, representing a gain of 17 times in spectral efficiency.¹⁷

¹⁶ Source: CTIA's Wireless Industry Indices, Semi-Annual Data Survey Results: A Comprehensive Report from CTIA Analyzing the U.S. Wireless Industry, Year-End 2010 Results, released May 2011, at 167 ("CTIA Wireless Industry Indices Report").

¹⁷ Source: Rysavy Research, "Transition to 4G," September, 2010. http://www.rysavy.com/Articles/2010 09 HSPA LTE Advanced.pdf

Thus, over the twenty-four year period, voice capacity has increased by a multiplicative combination of cell site density ¹⁸ and voice spectral efficiency.

Cell site density gain = 277

Voice spectral efficiency gain = 17

Total network capacity gain for voice since 1985 = 277 X 17 = 4,708

It should be evident that cellular architectures represent a configuration that is capable of providing tremendous service capacity to its users. Understanding the benefits of a cellular architecture, we can now examine the services it can deliver in greater detail.

Services Delivered

One would expect that a high density of cell sites combined with spectrally efficient technologies would result in today's networks supporting large service volume. That is indeed the case, which we can demonstrate by examining voice minutes, text messages, and data consumption.

Voice Minutes

As of the third quarter of 2009, US subscribers were consuming 793 minutes of voice per month, more than 13 hours per month, as shown in Figure 8.¹⁹ Not only is this an astonishing amount, but it is more than twice as much as the next leading country, Urkaine.

¹⁸ Continuing to aggressively add traditional large-coverage area (macro) cell sites is not necessarily practical due to the expense involved and logistical challenges such as zoning. It is much more cost effective to add capacity using additional spectrum. Small-coverage solutions such as femtocells and picocells, however, will play an important role in continued expansion of capacity.

¹⁹ Bank of America, Merrill Lynch, Global Wireless Matrix 4Q09.

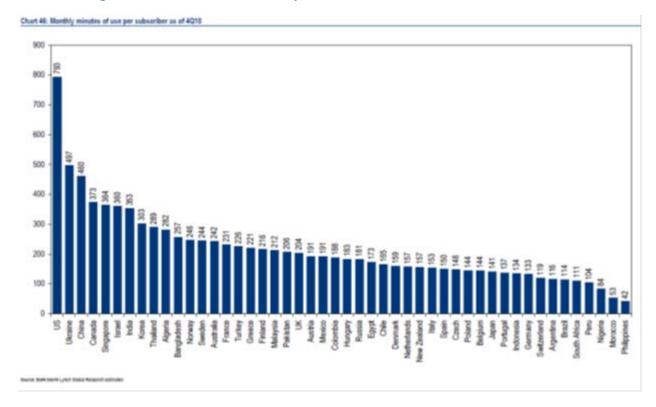


Figure 8: Minutes of Use of Voice per Month Across Different Countries

In CTIA's most recent Semi-Annual Wireless Industry Survey, the total number of minutes consumed in 2010 added up to more than 2.24 trillion in the second half of 2010, equating to more than 6.1 billion minutes of use per day.

Another way of looking at services rendered is through the total number of wireless connections as shown in Figure 9. This shows consistent and steady growth year after year, a further indication of extracting the greatest possible value from the spectrum used.

Estimated Subscriber Connections 350,000,000 255,395,599 300,000,000 233,040,781 250,000,000 200,000,000 150,000,000 100,000,000 11,032,753 7,557,148 50,000,000 140,213 Year-End 2010 Estimated Wireless Connections Up More than 17 Million from December 2009 Materials May not be reproduced or photocopied in any form without written permission from CTIA @ 2011 CTIA-The Wireless Association® Source: CTIA

Figure 9: CTIA Estimates on Wireless Connections²⁰

Message Volume

As reported in CTIA's semi-annual survey, more than 2.05 trillion text messages were sent and received on U.S. networks in 2010, reaching 6 billion messages per day by the end of the year. During 2010, users also sent 56.6 billion multimedia messages, more than one and a half times the 34.5 billion messages in sent the prior year.

Data Volume

On many networks, data traffic already accounts for sufficiently more volume of bits transmitted than voice. 21 Yet, we are only in the earliest stages of data consumption. Cisco projects mobile

²⁰ Source: CTIA's Wireless Industry Indices, Semi-Annual Data Survey Results: A Comprehensive Report from CTIA Analyzing the U.S. Wireless Industry, Year-End 2010 Results, released May 2011, at 167 ("CTIA Wireless Industry Indices Report").

broadband traffic approximately doubling for the next five years, as shown in Figure 10, measuring global volume by exabytes (billions of gigabytes) per month.

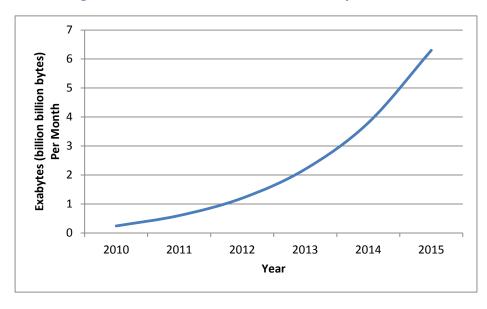


Figure 10: Global Mobile Broadband Data Projection²²

Much of the volume on today's network is from smartphones. In 2009, Nielsen reported the average iPhone user consuming 400 Mbytes per month.²³ Meanwhile, Clearwire indicated in March 2010 that their mobile WiMAX subscribers are consuming 7 GBytes per month.²⁴ Emerging new devices such as netbooks and tablets will further increase data volume.

Supporting current and projected levels of data volume is only possible with extremely efficient use of spectrum. The wireless industry has no choice but to be efficient. And even with efficient

²¹ Source: Rysavy Research, "Transition to 4G," September, 2010. http://www.rysavy.com/Articles/2010_09_HSPA_LTE_Advanced.pdf

²² Source: Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010-2015," February1, 2011.

²³ Source: Edible Apple, "Average iPhone user consumes 400MB of data every month," June 17, 2009.

²⁴ Source: Fierce Wireless, March 15, 2010. http://www.fiercewireless.com/story/clearwire-mobile-wimax-subs-eating-7gb-month/2010-03-15

technologies and deployment, current spectrum allocations are likely to become severely challenged in the next three to five years.²⁵

Application Efficiency

So far, this paper has concentrated on how efficiently services are delivered by the wireless network. But one must also consider the efficiency of the services and applications themselves. It is equally important for developers to optimize the efficiency of their services and applications for the mobile network and device, and there are examples to this effect:

- Wireless E-mail Efficiency. The leading wireless e-mail systems employ multiple methods to minimize the amount of data communications including data compression, ability to partially view attachments without downloading the whole file, and "pushing" messages so clients do not have to constantly poll for new data.²⁶
- Video Efficiency. Video can consume more data than any other applications and is increasingly embedded in consumer and business applications. Today's mobile video encoding systems use the most advanced compression algorithms available such as H.264/MPEG 4 Part 10 Advanced Video Coding. Moreover, operators are providing guidelines on how to deploy efficient video delivery applications.²⁷
- Mobile Optimized Web Sites. Nearly all major websites nowadays have a mobile version of the
 content that is automatically provided to mobile devices. There are also vendors (e.g.,
 Bytemobile, Opera) that provide Web optimization gateways with which operators can make
 subscriber Web access more efficient.
- **Mobile Middleware.** There are multiple vendors of sophisticated software components that reside on mobile devices and in gateways to streamline communications of data over the radio

²⁵ Source: Rysavy Research, "Mobile Broadband Capacity Constraints And the Need for Optimization," February 24, 2010.

²⁶ For further details, refer to the Rysavy Research report, "Wireless E-Mail Efficiency Assessment," January 27, 2009. See http://www.rysavy.com/Articles/2009 01 27 Rysavy EMail Efficiency.pdf.

²⁷ For example, on March 30, 2010, AT&T presented the Webcast "Development Best Practices for Video Streaming over the AT&T Mobile Network" and supplies an accompanying white paper. For further information, see: http://developer.att.com/developer/index.jsp?page=webcast&id=6.3 v1 9700344.

link.²⁸ These middleware systems dramatically reduce the amount of communicated data through methods such as data compression, intelligent local caching of data, and combining multiple small requests into a single larger request. In addition, these systems can implement policies to select the appropriate network (e.g., Wi-Fi versus 3G) for different types of operations.

Both the Internet and mobile broadband industries are being driven by social network sites such as Facebook, sites providing entertainment, news, and sports, and on-demand video applications such as YouTube. While it would be theoretically more efficient from a spectrum perspective if everybody watched the same thing at the same time, the fact is that millions of people want to watch what they want, when they want. An increasing amount of video content is now available on demand whether from television networks or services such as Amazon, Hulu, iTunes, and Netflix. With these, users can time shift and place shift their viewing, making their lives more flexible. Users also want to surf the Internet, download files, and stay connected to family and friends. Today's mobile broadband networks, due to their efficient use of spectrum, support this preference.

Conclusion

This paper has assessed how efficiently operators are using commercial-mobile-radio-service spectrum in the U.S. By every measure presented, the wireless industry is making extremely efficient use of spectrum. At a radio level, the industry is employing technologies that are as spectrally efficient as is practical. Evolution from 3G to 4G includes a steady series of improvements in spectral efficiency. Technologies are approaching the theoretical limits of spectral efficiency.

Beyond the radio level, cellular networks achieve extraordinary capacity through frequency re-use. Ever more cell sites, now numbered in the hundreds of thousands, allow operators to efficiently deliver a wide array of services to hundreds of millions of subscribers. The cellular approach results in much higher bits per second per coverage area than alternate wireless architectures such as broadcast-television networks.

The U.S. wireless industry is a world leader in service delivery, with more than twice the number of minutes per subscriber per month, and with the highest overall industry revenue. Wireless applications themselves are increasingly being designed for efficient use, thus minimizing the impact on the network and allowing greater numbers of users to enjoy the network.

²⁸ Examples of vendors include Antenna Software, Sybase, NetMotion Wireless, and Oracle. For further details on how these systems work, refer to the Rysavy Research report, "Harnessing Mobile Middleware," December 19, 2007, http://www.rysavy.com/Articles/2007 12 Harnessing Mobile Middleware.pdf.

Innovation is not standing still. The industry is working on standardizing and deploying promising new approaches to further extract usage from available spectrum. While none of these techniques will obviate the need for additional spectrum, they demonstrate the U.S. wireless industry's unparalleled commitment to innovation and efficiency.